ELECTRON CLOUD OBSERVATIONS: A RETROSPECTIVE

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Abstract

The study of electron clouds in high-intensity storage rings remains an important area of R&D 30 years after the first observations were made. The list of cloud-induced effects continues to grow as new observations are reported. Data from dedicated electron cloud diagnostics, used in combination with standard beam diagnostics, have contributed to a better understanding of the physics of the electron cloud and its interaction with the beam. Examples of electron cloud observations have been selected from the published record to highlight various important aspects of the physics. Comparisons of data among various rings show interesting similarities and differences. Such data, used in combination with modeling and analytical calculations, more fully characterize the electron cloud distribution and help to identify cures. Rather than attempt to be comprehensive, this paper is meant to illustrate what we have learned and what needs to be better understood.

INTRODUCTION

"Retrospective" has two meanings: 1. Looking backward; contemplating things past; and 2. An exhibition of a representative selection of an artist's life work. This paper is an attempt to contemplate the body of work of the electron cloud "artists" – all those who have contributed to the understanding of the EC phenomenon.

Considerable progress in understanding electron clouds has been made since 1995, when a beam-photoelectron instability – then known as the "Ohmi" effect – was first described [1,2]. Electron-induced effects are not entirely new; they were observed 30 years previously in small, medium-energy proton storage rings [3-5]. It is now clear that low-energy, background electrons (the "electron cloud") are ubiquitous in high-intensity particle accelerators and storage rings. Whether or not the electron cloud (EC) degrades the beam depends on many factors. Many review articles have been written that document observations and understanding of EC generation and effects, especially over the past decade [6-13].

In this paper, no attempt is made to fully review the subject, but rather to highlight EC diagnostics and observations that have contributed to a better understanding of the physics of EC effects. After a brief introduction to the origins and nature of the electron cloud, dedicated diagnostics used to characterize both the cloud and beam-cloud interactions are described. Selected observations in different storage rings are discussed and compared. Examples are drawn heavily from the published literature, including papers presented at special international workshops [14-18] or special sessions at the major particle accelerator conferences. These experimental data can be used to provide realistic limits on key input parameters for modeling efforts and analytical calculations, thereby improving their predictive capability.

ELECTRON CLOUD

Origins

The distribution of the electron cloud will depend on which electron production mechanisms dominate in a given ring. Primary electrons can be produced directly by irradiation of the vacuum chamber surfaces by synchrotron radiation (in this case known as photoelectrons), ions, or beam particles, or by ionization of the residual gas. Indirectly, bombardment of the chamber surface by electrons accelerated by the beam can lead to the production of secondary electrons. A review of secondary electron generation can be found in [19], while detailed measurements and theory of photoelectron and secondary emission properties can be found in [20-25].

Amplification of the electron cloud can occur under certain operating conditions. Key contributing factors include beam parameters such as bunch current and spacing, photoelectron and secondary-electron yield coefficients, and the vacuum chamber geometry and surface condition. Secondary emission can dominate through a runaway condition generally referred to as beam-induced multipacting [5,26,27]. Electrons can become trapped in spurious magnetic fields, such as the distributed ion pump (DIP) leakage field [6], or in quadrupole magnets. There are many other subtle yet important details that can be found in the references. If the cloud density becomes sufficiently large, the beam-cloud interaction can seriously degrade accelerator performance.

Effects on the Beam

Electron cloud-induced effects on the beam take numerous forms. These include cloud-induced noise on beam diagnostics (e.g., wire scanners, ion profile monitors, etc.), vacuum and beam lifetime degradation through electron-stimulated gas desorption, and heat deposition on cryocooled components. Collective instabilities are also observed, e.g., vacuum pressure bump instability, electron-proton instability (coupled oscillations), transverse coupled-bunch instability (due to electron cloud "wake"), and a fast "head-tail"-like single-bunch instability that results in emittance blow-up and luminosity degradation. Finally, the electron cloud can enhance other effects, such as the beam-beam effect [6-10,13].

EC DIAGNOSTICS

Active programs in electron cloud cures began at PEP-II (Stanford Linear Accelerator Center) [28] and KEK-B (High Energy Accelerator Research Organization (KEK), Japan) [29] B-factories while both were under develop-

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ment. Predictions of beam-induced multipacting in the Large Hadron Collider (LHC), also under development at the time, resulted in a crash program at CERN to avoid deleterious EC effects [30]. Codes were developed for all three rings to model EC generation and instabilities [13]. Soon thereafter, efforts were undertaken at the Advanced Photon Source (APS) (Argonne National Laboratory) to directly measure and characterize the EC distribution in detail using specially designed dedicated detectors [26]. Detailed EC measurements were also undertaken at the Proton Storage Ring (PSR) (Los Alamos National Laboratory) [31].

Standard beam diagnostics such as beam position monitors (BPMs) and vacuum pressure can give indirect evidence of EC effects. These diagnostics usually give the first indication of ECs. However, for the purposes of understanding the physics, these cloud-induced signals can in fact be difficult to quantify, and indirect evidence of ECs is not always convincing [31].

The APS pioneered the use of the planar, retarding field analyzer (RFA) [32]. This device measures the electron flux at the chamber wall as a function of integrated electron energy. The RFA has several advantages over biased electrodes, such as beam position monitors or striplines. The RFA collector is graphite coated, minimizing secondary emission, and the retarding field is shielded from the beam. The EC wall flux and collision energy distribution can be directly quantified. It is remarkable how much can be deduced from these data, especially from the energy distribution, including details of the beam-cloud interaction and the chamber surface characteristics. These data are being used to better benchmark the codes. It is very difficult to deduce the true wall flux, let alone the distribution, using biased electrodes. Varying the bias voltage on an electrode changes the electron collision energy and, thus, the secondary emission from the electrode surface. The collection length also varies with bias voltage as electrons are drawn from a greater volume.

At PSR, the RFA design was improved by adding an amplifier and a sweeper to measure the time structure of the EC [31]. At the Super Proton Synchrotron (SPS) at CERN, the RFA design was adapted to measure the EC within the field of a dipole magnet [30]. RFA-type detectors have been installed in numerous rings.

The RFA is limited to measuring the EC flux at the chamber walls. Bunch-by-bunch tune measurement diagnostics were first used at KEKB to quantify the EC at the center of the beam by measuring the tune shifts induced by the cloud [29]. EC-induced single-bunch instabilities are detected by measuring the bunch-by-bunch beam size, e.g., in PEP-II [28].

EXPERIMENTAL OBSERVATIONS

A summary paper on EC observations cannot hope to be comprehensive. Rather, the experimental record for different high-intensity storage rings was scanned for data that highlight various important aspects of the physics of electron clouds and effects. The selected observations examine: cloud build-up and saturation, vacuum pressure rise, surface conditioning, longitudinal dependence, secondary-electron vs. photoelectron dependence, EC in dipole fields, multipacting in a medium-energy long-pulse proton ring, the electron decay time, and a comparison of EC-induced collective effects.

For positron rings, the electron cloud can build up over multiple-bunch trains, especially if the beam-induced multipacting condition is satisfied. It is interesting to compare results at KEKB (per tune shift) [29] and APS (per RFA) [26]. The cloud is observed to build up and reach a saturation level after 20-30 bunches in both rings. These results are consistent with modeling results in which space-charge effects that limit the multipacting exponential growth are included. The chamber cross-sections are similar, except that the APS chamber includes an antechamber. EC buildup was observed at KEKB for bunch spacing varying from 4-16 ns, whereas for APS, maximum buildup was observed for 20-ns bunch spacing. It turns out that EC amplification is a rather more complex phenomenon than what has been understood as beam-induced multipacting [33,34]. This author prefers to use the term "beam-induced amplification," coined by L. Lioacono (Loyola U.)

"Runaway" vacuum pressure rise has been reported in many rings: PEP-II, KEKB, SPS, APS, and the Relativistic Heavy Ion Collider (RHIC) (Brookhaven National Laboratory). The data from PEP-II are quite interesting [28]. Above a beam current threshold of 700 mA, the pressure rises by over an order of magnitude up to a current limit of 1200 mA. When the solenoidal windings are energized, producing a longitudinal magnetic field that confines the EC at the walls (a standard cure), the pressure rise is reduced by half. Above 1200 mA, the pressure actually begins to drop, whereupon up to 1400 mA can be stored. This implies resonant-like behavior that needs to be explained.

A key parameter governing secondary emission is the secondary electron yield coefficient δ. This parameter depends on the electron's incident energy and angle, the chamber surface material, and surface conditioning. Irradiation by photons or electrons conditions the surface and serves to reduce δ over time, thought to result from removal of the oxide layers and other changes in the surface chemistry. Bench measurements at CERN [16,20] show that δ for Cu is reduced by a factor of two (from 2.4 to 1.3) after an electron dose of 10^{-3} C/mm^2. These results are consistent with measurements at APS that show that the wall flux (per RFA) on the Al chambers was reduced by a factor of two after 60 Ah of operation; this can be converted to an electron dose of about 10^{-3} C/mm^2 [26].

Most EC models use a 2D assumption to simplify the computation. In most cases, this is sufficient because the force on the EC from the beam is transverse. However, the data at APS and PSR show marked azimuthal variations in the cloud [26,31]. At APS, EC density variations up to a factor of four were observed over a 4-m field-free chamber length. Local electron sources such as photoemission from synchrotron radiation absorbers or secondary electrons from an H- stripper foil result in azimuthal density variations that can affect the beam-cloud interaction. Modeling of the EC in a solenoid using a 3D PIC code and including space charge by L. Wang and colleagues also shows complex longitudinal dependence [35].

The early results in the KEK Photon Factory [1] were reproduced in the Beijing Electron Positron Collider (BEPC) (Institute of High Energy Physics (IHEP), P.R. China) [36] (both in positron beams). Installation of RFAs at BEPC afforded an opportunity to compare it with APS. No multipacting was observed at BEPC, compared to strong evidence of multipacting at APS. The results suggest that photoelectrons dominate in BEPC, and the cloud saturates immediately with a single bunch. On the other hand, secondaries clearly dominate at APS. These observations are consistent with the fact that only the APS chamber has an antechamber; both chambers are made of Al, which has a relatively large δ.

A special chamber was installed at the SPS to measure the electron cloud in a dipole field [37]. The detector is an RFA-type, with several strip detectors located behind a grid of small holes drilled into the bottom surface of the chamber. The data qualitatively confirm simulation results that show high-density vertical stripes in which electrons are confined to move along the dipole field lines. These data for the first time confirmed a prediction made by modeling results by M. Furman and G. Lambertson [38] and F. Zimmermann [39]. Although this success gives reason for cautious optimism, in most cases, EC and instability modeling have explained experimental observations after the fact.

The EC phenomenon in the PSR is rather different from short-bunch positron or proton rings. Cloud electrons are trapped in the long PSR proton bunch and can be accelerated into the wall only as the tail of the bunch passes, giving rise to "trailing edge multipactor." An RFA was modified with an amplifier, and mounted opposite a curved electrode that can be biased with a high-voltage pulse [31]. By varying the time of the pulse relative to the bunch passage, a significant fraction of the electron cloud in the gap can be directly measured. Intriguing results were found; for example, the saturation and dependence on beam parameters and instability thresholds of the "prompt" electrons and "swept" electrons differ.

Measurements of the nature of electron clouds indicate that their lifetime in the chamber after a bunch passage exceeds previous expectations. The decay time of the electron cloud has been measured at PSR [31] and KEKB [29] using different techniques. At PSR, the "swept" electron signal was measured as a function of time after the beam was extracted. The data show a decay time of 170 ns, which implies that the zero-energy secondary emission coefficient _$_0$ is ~0.5 (i.e., very-low-energy electrons are "reflected" by the wall) (the PSR chamber is SS; CERN Cu data give _$_0$ ~0.8 [40]). At KEKB, the tune shift of a test bunch was measured as a function of its distance after a bunch train. These data gave a decay time of 30 ns. In a second experiment, the bunch sizes (emittance blowup) in two bunch trains separated by a gap were measured. The bunches in the second train blew up earlier in the train, and suggest a decay time longer than 64 ns. There may possibly be two different mechanisms governing the EC decay time. One area of interest is to study the possible trapping of electrons in quadrupole magnet fields. Simulations by M. Pivi and his colleagues suggest that such trapping can significantly increase the electron cloud lifetime in PEP II. Plans are underway to measure this trapping directly in an experiment at PSR, in collaboration with R. Macek.

There remain areas of electron cloud phenomena that are poorly understood. The combined phenomena, or possible enhancement, of beam-beam and EC effects has been postulated (E. Perevedentsev, K. Ohmi, and A. Chao (2002)). The combined effect of EC and ordinary geometric wakes has not been studied in detail. Finally, ideas have been put forth to use microwaves as a diagnostic or suppressor of electron clouds (S. Heifets, A. Chao, F. Caspers, and F.-J. Decker.) Interesting preliminary results are described by T. Kroyer (CERN) at this workshop.

Finally, observations of electron-cloud-induced beam instabilities vary among a number of storage rings. Table 1 gives a brief summary of the type of instability (single-bunch or coupled-bunch) and whether it appears in the horizontal or vertical plane. These observations should be studied more closely to fully understand the differences.

Table 1: EC-driven collective effects

	Horizontal plane	**Vertical plane**
KEK PF	–	Coupled bunch (CB)
BEPC	–	CB
KEKB LER (e+)	CB	CB; single bunch
CESR	CB (DIPs)	–
PEP II LER (e+)	single	–
APS (e+)	CB	–
PSR	–	
SPS-LHC	CB	single
PS-LHC	single	–
DAΦNE	(likely below	threshold)

CURES

The most straightforward way to avoid EC amplification is through the choice of bunch spacing, bunch current, and chamber height. This solution is not always desirable or practical. The next choice is to condition the chamber surfaces or apply surface coatings that minimize δ; e.g., TiN or TiZrV. In rings that suffer from photoemission, the design goal is to minimize photoelectron yield through chamber geometry (e.g., antechamber, normal incidence). In the B-factories, a very successful cure has been the solenoidal windings to keep emitted secondary electrons confined near the wall, away from beam. However, this cure works only in rings dominated by ECs in field-free regions (i.e., *not* in the dipoles). If passive cures prove insufficient, one may consider implementing fast beam feedback if the instability growth rate is sufficiently low.

Contributions to understanding EC effects come from a growing community beyond accelerator physics. Modeling efforts and benchmarking continue to be refined as more physics is added from vacuum and surface chemistry, plasma wakefield accelerator physics and computational methods, heavy ion fusion, photocathode materials science, and photoinjectors. In the latter case, modeling of the electron dynamics in megavolt fields in photocathode rf guns requires an accurate photoelectron distribution. This may appear counterintuitive, since the emitted electrons typically have energies of only a few volts. Likewise, modeling results for beam-induced multipacting in the APS also depend strongly on the assumptions of the secondary distribution [26,33].

ELECTRON BEAMS

It is worth mentioning negatively-charge beams. Circa 1997, J. Galayda suggested that under the right conditions, electron clouds can impact electron beams as well. At the APS, a multipacting-like bunch-spacing dependence of the electron cloud is observed for electron beams, but the effect is a factor of ten smaller than for positrons and occurs at a bunch spacing of 30 ns. The average electron energy measured at the wall is also ten times smaller for electron beams, compared with positrons (10 eV vs. 100 eV). This last comment implies that the cloud electrons never drift as close to the center of the electron beam as for positrons.

However, an anomalous pressure rise was observed with electron beams at APS. During a scan of bunch patterns, bunch trains of length $4\lambda_{rf}$ (11.4 ns) separated by $2\lambda_{rf}$ (5.7 ns) resulted in twice the vacuum pressure, half the beam lifetime, and RFA signals three to five times higher than when the same bunch trains were separated by $12\lambda_{rf}$ (34 ns). It may be possible to understand these results using the phenomenological map method introduced by U. Iriso (BNL) at this workshop. When the experiment was repeated one year later, the effect disappeared, presumably due to surface conditioning [26].

There are plans to install a superconducting insertion device at the APS. Preliminary calculations of the power deposition on the walls due to the electron cloud give up to 1 W/m *with an electron beam* (Al, four times less with TiN). It is hoped that these calculations can be verified in the future using RFAs installed in a chamber with the appropriate cross section. The code used, POSINST, was written by M.A. Furman, M. Pivi, and colleagues, and has been benchmarked for both positron and electron beams at APS [33,41].

SUMMARY

Electron cloud effects are increasingly important phenomena in high-luminosity, high-brightness, or high-intensity accelerators and storage rings. Designs of future colliders, storage rings, damping rings, and heavy ion beams may be impacted to avoid deleterious EC effects. Dedicated electron cloud diagnostics have contributed greatly to better understanding of electron cloud generation and the importance of key parameters such as the secondary electron yield coefficient and the secondary energy distributions in modeling efforts. Interesting comparisons can be made between various storage rings to study similaries and differences in the nature of the electron cloud and interaction with the beam.

Surface conditioning and use of solenoidal windings *in field-free regions* are successful cures. The question is: will they be enough? In rings that appear dominated by EC effects in the dipoles, cures may involve additional creative solutions.

More work needs to be done in areas not well understood. For example, what is the effect of a 3D electron cloud density variation on instability thresholds? How can we explain the differences in cloud lifetime between different rings? What are the combined effects of ECs and other dynamics, such as beam-beam effects in colliding rings? Finally, are there any new possible effects, perhaps longitudinally, induced by the electron cloud? What are the dominant EC effects in electron beams and how do their thresholds compare with positron beams?

We should continue to develop and implement electron cloud diagnostics, especially in magnetic fields, and continue to refine the models based on measured data. Ideally, on further study of electron cloud effects and observations, we can begin to develop scaling laws or figures of merit to aid in the design of future accelerators.

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